Int J Life Cycle Assess (2016) 21:176–189
DOI 10.1007/s11367-015-1008-2



# Life cycle assessment of waste treatment strategy for sewage sludge and food waste in Macau: perspectives on environmental and energy production performance

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Received: 29 May 2015 / Accepted: 13 November 2015 / Published online: 27 November 2015


**Abstract**
*Purpose* This study evaluates waste treatment scenarios involving the current waste treatment method (i.e., incineration) and two proposed technically feasible treatment methods (i.e., anaerobic digestion and co-digestion) for sewage sludge and food waste, with the consideration of environmental impacts and energy production performance. A sustainable waste treatment strategy is then identified through a combination of waste treatment methods with low environmental impacts and high energy production in Macau.
*Methods* This study applies life cycle assessment methodology. The selection of waste treatment methods is based on Macau's situation (i.e., land scarcity and limited agricultural activities). Scenarios with different treatment methods are evaluated based on human health, ecosystems, and energy production performance. This study is divided into three parts. In part 1, three scenarios for treating sewage sludge and food waste are evaluated including existing incineration, anaerobic co-digestion, and a combination of existing incineration and anaerobic digestion. In part 2, two scenarios are assessed for treating the remaining food waste. In part 3, a proposed waste treatment scenario through a combination of waste treatment methods is identified based on the results from part 1 and part 2. The scenario is compared with the existing incineration scenario for treating all sewage sludge and food waste generated in Macau. Furthermore, a study is conducted to evaluate the condition with increased sewage sludge after the wastewater treatment plants are upgraded.
*Results and discussion* In part 1 and part 2, anaerobic co-digestion scenario and anaerobic digestion scenario (i.e., for remaining food waste) outweigh other scenarios with the lowest environmental impacts and highest energy production. With the combination of these two selected scenarios, the proposed waste treatment scenario improves the performance in human health, ecosystems, and energy production by 36, 13, and 61 %, respectively, compared with the existing incineration scenario in Macau. Moreover, the proposed scenario also has better performance even if the generation of sewage sludge increases. The environmental performance of proposed scenario is almost two times better than the existing incineration scenario in human health categories.
*Conclusions* In this study, a proposed waste treatment strategy for sewage sludge and food waste in Macau is suggested with low environmental impacts and high energy production performance. The proposed waste treatment strategy includes a combination of anaerobic co-digestion and anaerobic digestion treatment method. The result of this study could serve as a reference to other urbanized countries or cities for sustainable treatment of sewage sludge and food waste.

**Keywords** Anaerobic co-digestion · Anaerobic digestion · Food waste · Incineration · Life cycle assessment · Sewage sludge

Responsible editor: Shabbir Gheewala

**Electronic supplementary material** The online version of this article (doi:10.1007/s11367-015-1008-2) contains supplementary material, which is available to authorized users.

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## 1 Introduction

With rapid population growth and urbanization, the increase of sewage sludge and food waste generation has become inevitable. Attention should be paid to these wastes as they represent a large portion of biodegradable waste generated in urbanized cities (Righi et al. 2013). Improper management of sewage sludge and food waste creates negative impacts on the environment, such as emitting odorous compounds into the atmosphere, introducing moisture to the incineration process and deteriorating the quality of leachates from landfills (DEFRA 2000; Lee et al. 2007). On the contrary, these wastes can be valuable resources if they are well managed and recycled (Kim and Kim 2010). In order to promote environmental sustainability and better recourses utilization, an astute waste treatment strategy on sewage sludge and food waste is considered an absolute necessity (ISWA 2013).

In Macau, the annual productions of sewage sludge and food waste are 0.03 and 0.21 tonne per capita in 2012, respectively (DSEC 2012). Compared to other Asian places with developed economies such as Taipei City, Seoul, and Singapore, Macau has the highest amount of food waste generation (MoE 2012; HKEB 2014; NEA 2014). In common, Taipei City, Seoul, and Singapore have long developed their own food waste management strategies in order to reduce the food waste generation, while the development of food waste management strategy in Macau is still in its preliminary stage. Due to this circumstance, the Government of the Macau Special Administrative Region of the People's Republic of China has published a document entitled "Environmental Protection Planning of Macau (2010–2020)" to put forward a strategic and directive framework of environmental protection (DSPA 2012), one of the main focuses on planning a sustainable food waste treatment and introducing technologies and strategies for the reutilization of sewage sludge in a low pollution, low emission, and environmentally friendly way. Hence, the identification of a suitable waste treatment method for treating sewage sludge and food waste is necessary for cities with the initiative to develop a sustainable waste treatment strategy.

Up to date, there are several options available for the treatment of sewage sludge and food waste such as landfilling, composting, incineration, anaerobic digestion, and anaerobic co-digestion (Rosenberg 1997; Güereca et al. 2006; Xu et al. 2014). However, for the sake of land scarcity and limited agricultural activities in urbanized cities like Macau, landfill and composting are not considered as feasible waste treatment methods. Currently in Macau, sewage sludge and food waste are combusted together with municipal solid waste (MSW) with electricity generated during the incineration process. However, the maximum treatment capacity of the incinerator will soon be reached and it is reasonable to separate and treat sewage sludge and food waste in order to reduce the loading of the existing incinerator. Moreover, waste having high moisture content such as sewage sludge and food waste is not suitable for incineration (Bolin 2010). Anaerobic digestion is a viable option for treatment of sewage sludge and food waste to produce biogas for energy generation. In addition, some studies suggested that sewage sludge and food waste can be anaerobic co-digested to increase the production of biogas (Sosnowski et al. 2003; Krupp et al. 2005). Several co-digestion plants have been successfully built and have been operating in different countries at present (Braun and Wellinger 2009).

Considering the environmental consequences and the resource recovery performance from different waste treatment methods, a decision analytical tool is required to evaluate the methods in order to generate decision criteria and formulate a treatment framework. Life cycle assessment (LCA), which is a scientific and quantitatively approach, is applied in this study to evaluate the existing and proposed waste treatment methods in Macau based on their environmental impacts and resource recovery performance (in terms of energy production performance). The LCA approach has been applied in some recent studies to investigate the global warming potential and environmental impact of various organic waste treatments (Yoshida et al. 2012; Righi et al. 2013; Kim et al. 2013). However, none of them provided a comprehensive study covering all co-treatments for sewage sludge and food waste in an urbanized city with minimal agricultural activities. It is important to consider the environmental consequences and energy production performance from sewage sludge and food waste treatment in order to suggest a sustainable waste treatment strategy to fulfil the objective of reutilizing different forms of waste. Therefore, the objective of this study is to evaluate waste treatment scenarios which involves the current waste treatment method (i.e., incineration) and two proposed technically feasible treatment methods (i.e., anaerobic digestion and co-digestion) for sewage sludge and food waste, with the consideration of environmental impacts and energy production performance using LCA and identify a waste treatment strategy for sewage sludge and food waste through a combination of waste treatment methods in Macau.

## 2 Methodology

This study applies a LCA approach with international standard methods ISO 14040 and 14044 (ISO 2006a, b). LCA methodology consists of four phases and they are (i) goal and scope definition, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment (LCIA), and (iv) interpretation.

### 2.1 Goal and scope definition

The goals of this study are to evaluate the existing and proposed waste treatment methods for sewage sludge and food waste by investigating their environmental and energy production performance and to suggest a sustainable waste treatment strategy for the future. The environmental impacts from maintenance and replacement of equipment as well as construction and demolition of a waste treatment facility are usually considered to have a lower environmental burden than the direct emissions and the avoided impacts from the operational phase of the facility (Gentil et al. 2010). Therefore, this study only focuses on the environmental impacts from the operational phase of the waste treatment facility. The study is divided into three parts. The scenario descriptions and the explanations of abbreviation for each part are presented in Table 1. In part 1, three waste treatment scenarios (i.e., EI (SS+FW) represents the existing incineration of sewage sludge and food waste with MSW, coAD (SS+FW) represents the anaerobic co-digestion of sewage sludge and food waste, and EI&AD (SS+FW) represents the incineration of sewage sludge and anaerobic digestion of food waste) are evaluated. Due to data unavailability, operational data of an existing anaerobic co-digestion plant for sewage sludge and food waste are collected from Yongyeon Wastewater Treatment Plant in South Korea (Ejlertsson and Magnusson 2013). The reasons for choosing the South Korean plant over the others are justified as follows: (1) the technology of the South Korean plant is more advanced since it was reconstructed for anaerobic co-digestion in 2010, which could be a good reference as the proposed plant in Macau; and (2) Macau and South Korea citizens have a similar Asian diet and thus the characteristics of food waste are similar. Since the food waste characteristics of Macau are unavailable from the literature, the food waste characteristics of Hong Kong, a city which has a similar dining style to that of Macau due to their close geographical location (i.e., Hong Kong and Macau are located in the southern part of Guangdong province of China), are compared with those of South Korea. The food waste characteristics of Hong Kong and South Korea are shown in Table A.1 in the Electronic Supplementary Material. A 10:3 mixing ratio by wet weight of sewage sludge and food waste is adopted in this study according to the same ratio applied by the South Korean plant. To ensure a fair comparison, this ratio is also applied to these three waste treatment scenarios evaluated in part 1. Since the amount of food waste generated is larger than that of sewage sludge in Macau, all sewage sludge is consumed and food waste remains after the treatments discussed in part 1 and the schematic diagrams of the system boundary are shown in Fig. 1. In part 2, two waste treatment scenarios (i.e., EI (FW) represents existing incineration of the remaining food waste with MSW, and AD (FW) represents anaerobic digestion of the remaining food waste) are evaluated for the remaining food waste and the schematic diagrams of the system boundary are shown in Fig. 2. In part 3, a proposed scenario with a combination of waste treatment methods is suggested based on the results from part 1 and part 2. It is further compared with the existing incineration scenario for treating all sewage sludge and food waste generated in Macau. Considering the increase of sewage sludge after the wastewater treatment plants are upgraded in Macau, a further study is conducted to evaluate the condition with increased sewage sludge.

### 2.2 Life cycle inventory

The identification and quantification of all the environmental inputs and outputs of the system boundary are represented by LCI. Local data on Macau are used whenever available. The data are mainly collected from the literature or government official websites and publications. When local data are unavailable, secondary data from other sources such as the literature and IPCC guidelines are applied with justification and assumption provided as clearly as possible for the application in Macau's situation. Data inventory for major processes such as incineration, anaerobic digestion, and anaerobic co-digestion are presented in Table 2. The data on the incineration process are collected from a field survey of existing incineration plant in Macau, which was previously conducted by Song et al (2013). Except greenhouse gas emissions, other emissions such as $NO_x$, $SO_2$, etc. from incineration are assumed to be process-specific and are based on the technology in the incineration plant (Doka 2003). As there is no existing anaerobic digestion plant in Macau, the local emission data or standard of the anaerobic digestion process are not available for this study. The data on the anaerobic digestion process refer to the emission standards of Organic Waste Treatment Facilities (OWTF) in Hong Kong from the environmental impact assessment (EIA) report of the Hong Kong government (HKEPD 2009). For the $CO_2$ emitted during anaerobic digestion, it is counted as biogenic and does not have any impact on climate change as suggested by IPCC guidelines (IPCC 2006). The inventory data on substrate composition and other treatment processes mentioned above are shown in Table A.2–A.5 in the Electronic Supplementary Material.

### 2.3 Life cycle impact assessment

Life cycle impact assessment (LCIA) is conducted using SimaPro 7.2.4 software with ReCiPe version 1.04 (Goedkoop et al. 2009). The ReCiPe is a commonly used impact assessment tool for LCA study of organic waste treatment (De Meester et al. 2012; Poeschl et al. 2012). Four midpoint impact categories, namely climate change,

**Table 1** Description of the waste treatment scenarios of each part in this study

| Functional unit | Scenario description | | |
|---|---|---|---|
| Part 1 | Scenario EI (SS+FW) | Scenario coAD (SS+FW) | Scenario EI&AD (SS+FW) |
| 1 tonne of sewage sludge and food waste mixture with a 10:3 mixing ratio by wet weight | Sewage sludge is dewatered to a dry matter content of 30 % and the dewatered sludge is transported to the existing incineration plant for MSW where it is combusted with all MSW including food waste. Electricity is produced during the incineration process. The fly ashes are treated by cement solidification and then disposed of at Kau Ou landfill. The bottom ashes are disposed of at Taipa landfill. | Food waste is separated from MSW and pre-treated by shredding before it is transported to the proposed anaerobic co-digestion plant, which also receives the dewatered sewage sludge from the sewage treatment plant. The biogas generated during the anaerobic co-digestion process is combusted to produce heat and electricity by the combined heat and power (CHP) unit. The remaining co-digestate is then transported to the existing incineration plant for combustion with other MSW. The ashes produced from incineration are treated in the same way as described in scenario EI (SS+FW). | Dewatered sewage sludge employs the current waste treatment method by combustion in the existing incineration plant with other MSW. Separated food waste is pre-treated and transported to the proposed anaerobic digestion plant for treatment. The biogas generated is used to produce heat and electricity by CHP unit while the digestate is used to produce compost for land application. The compost produced avoids the application of artificial fertilizers. |
| Part 2 | Scenario EI (FW) | Scenario AD (FW) | |
| 1 tonne of remaining food waste | The remaining food waste is combusted with other MSW in the existing incineration plant. Electricity is produced by incineration and the fly ashes and bottom ashes are disposed of at respective landfills as aforementioned. | A proposed anaerobic digestion plant is built to treat the remaining food waste. Heat and electricity can be generated by the biogas produced through the CHP unit. Digestate is used to produce compost. | |
| Part 3 | Scenario EI (all) | Scenario PS (all) | |
| All sewage sludge and food waste generated currently[a] | This scenario represents all sewage sludge and food waste generated is combusted with other MSW by using the existing incinerator in Macau. | This scenario represents a proposed waste treatment strategy through a combination of waste treatment methods based on the results from part 1 and part 2 for treating all sewage sludge and food waste generated in Macau. | |
| | Scenario EI (all+increased SS) | Scenario PS (all+increased SS) | |
| All sewage sludge and food waste generated after wastewater treatment plants are upgraded[b] | The amount of sewage sludge produced is increased after the wastewater treatment plants are upgraded in Macau. This scenario represents all sewage sludge (i.e., after wastewater treatment plants are upgraded) and food waste generated is combusted with other MSW by using the existing incinerator in Macau. | The amount of sewage sludge produced is increased after the wastewater treatment plants are upgraded in Macau. This scenario represents a proposed waste treatment strategy through a combination of waste treatment methods based on the results from part 1 and part 2 for treating all sewage sludge (i.e., after wastewater treatment plants are upgraded) and food waste generated in Macau. | |

*EI* existing incineration, *SS* sewage sludge, *FW* food waste, *coAD* anaerobic co-digestion, *EI&AD* existing incineration and anaerobic digestion, *AD* anaerobic digestion, *PS* proposed scenario, *all* all sewage sludge and food waste generated currently, *all+increased SS* all sewage sludge and food waste generated after wastewater treatment plants are upgraded

[a] The amount of sewage sludge is equal to 30 tpd and the amount of food waste is equal to 232 tpd

[b] The amount of sewage sludge is equal to 242 tpd and the amount of food waste is equal to 232 tpd

particulate matter formation, photochemical oxidant formation, and terrestrial acidification, are chosen as they are generally considered relevant and significant for waste treatment studies (Bernstad and la Cour Jansen 2011; Evangelisti et al. 2014). As defined by ReCiPe, damage categories namely human health and ecosystems are assessed for endpoint results. Climate change, photochemical oxidant formation, and particulate matter formation are categorized under human health by quantifying the midpoint impact to disability-adjusted life years, while climate change and terrestrial acidification are classified under ecosystems by quantifying the midpoint impact to loss of species during a year. Respective data are collected under different impact categories through the multiplication of specific characterization factors. The magnitude of intervention at the midpoint level is required for the quantification for the characterization of the endpoint damage (Goedkoop et al.

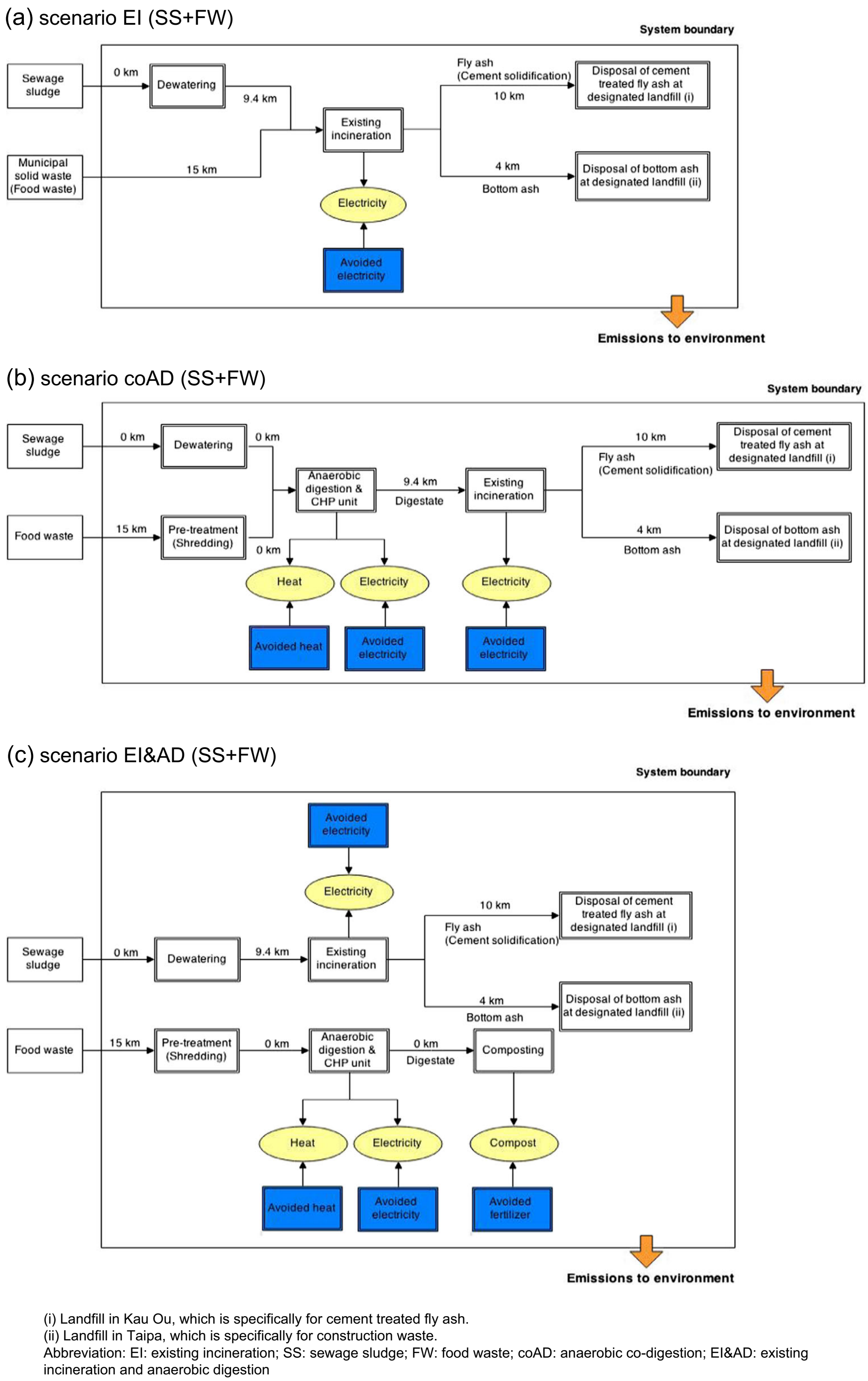
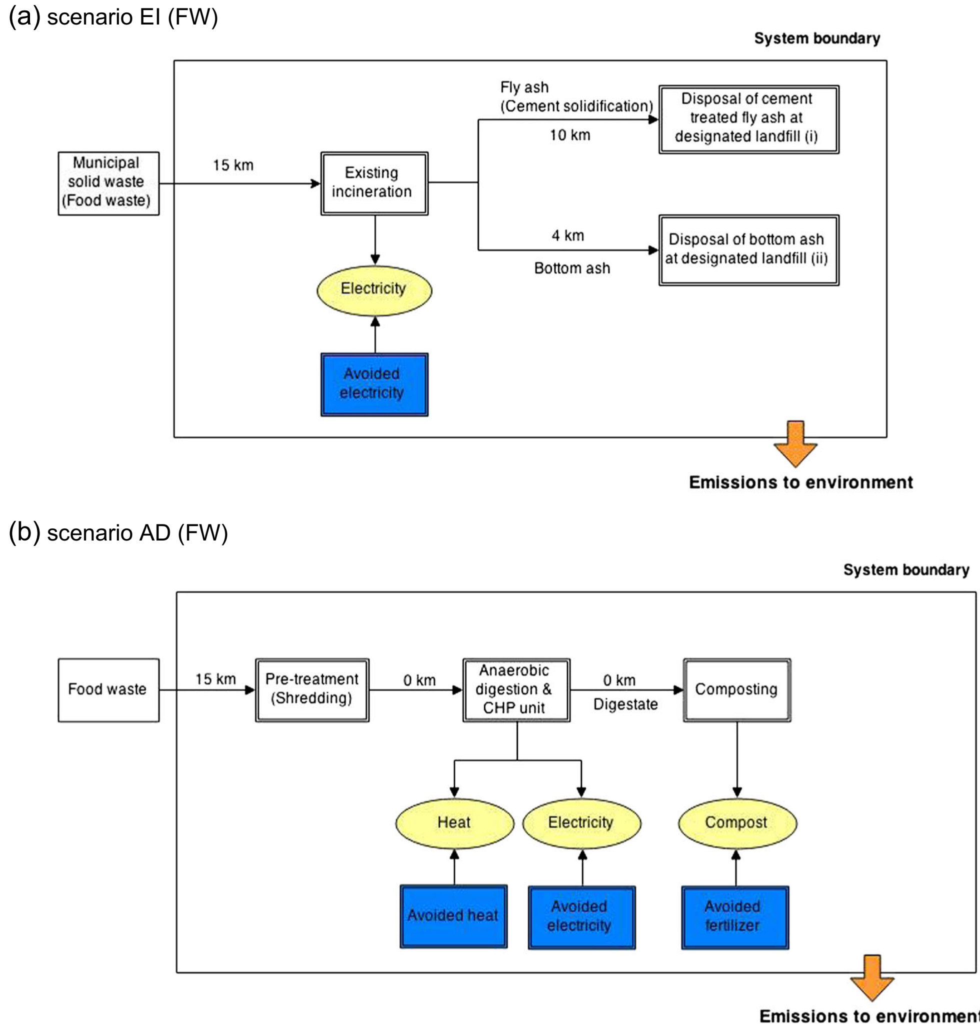



**Fig. 1** System boundary of **a** scenario EI (SS+FW), **b** scenario coAD (SS+FW), and **c** scenario EI&AD (SS+FW) in part 1. Transportation is not required for distance defined as 0 km in the above figures as the processes are operated in the same plants or locations

2009). In order to evaluate the energy production performance of the waste treatment methods, total energy production from each scenario is accounted for and used as an indicator by quantifying the energy production from the waste treatment processes to megajoule (MJ). Incineration and anaerobic digestion processes are responsible for producing energy within the scope of this study. In total, three indicators are considered in this




(i) Landfill in Kau Ou, which is specifically for cement treated fly ash.
(ii) Landfill in Taipa, which is specifically for construction waste.
Abbreviation: EI: existing incineration; FW: food waste; AD: anaerobic digestion

**Fig. 2** System boundary of **a** scenario EI (FW) and **b** scenario AD (FW) in part 2. Transportation is not required for distance defined as 0 km in the above figures as the processes are operated in the same plants or locations

study, namely human health, ecosystems, and energy production performance.

## 3 Results and discussion

### 3.1 Part 1: Selection of scenarios for sewage sludge and food waste treatment in Macau

#### *3.1.1 Part 1: Midpoint comparison in climate change and particulate matter formation*

Regarding the midpoint impact categories, climate change and particulate matter are the most significant impacts. The results of the climate change and particulate matter formation are presented in Fig. 3. The negative values indicate environmental benefits caused by avoided emissions from the system such as emissions from fossil fuel combustion to generate electricity. Scenario coAD (SS+FW) shows the best performance in both impact categories with a total value of $-1.05\times10$ kg $CO_2$ eq. and $1.20\times10^{-1}$ kg $PM_{10}$ eq., respectively.

For climate change, the impact from scenario coAD is due to the leaked biogas as fugitives emissions (IPCC 2006). The greenhouse gas $CH_4$, which has a global warming potential of 25 (Forster et al. 2007), is the major constituent of biogas. However, by referring to Fig. 3a, it is relatively small compared to the incineration process in scenario EI (SS+FW) and EI&AD (SS+FW). The most significant contribution to climate change during the incineration process is the $N_2O$ emission from the combustion of sewage sludge due to the high nitrogen content in sewage sludge (Svoboda et al. 2006; Shimizu and Toyono 2007). Meanwhile, $N_2O$ is a greenhouse gas

**Table 2** Summary of data inventory for incineration and anaerobic digestion process

| | Units (per tonne of waste) | Incineration | Anaerobic digestion and anaerobic co-digestion |
|---|---|---|---|
| Emissions to air | | | |
| $SO_2$ | kg | $1.0\times10^{-2}$[b] | $1.85\times10^{-2}$[f] |
| HCl | kg | $8.9\times10^{-3}$[b] | $3.71\times10^{-3}$[f] |
| $NO_x$ | kg | $2.4\times10^{-1}$[b] | $1.11\times10^{-1}$[f] |
| $NH_3$ | kg | $1.1\times10^{-2}$[b] | n.a. |
| CO | kg | $3.0\times10^{-2}$[b] | $2.41\times10^{-1}$[f] |
| Volatile organic compound (VOCs) | kg | $1.32\times10^{-1}$[c] | $3.05\times10^{-1}$[f] |
| HF | kg | $2.65\times10^{-2}$[c] | $3.71\times10^{-4}$[f] |
| Dioxins and furans | kg | $6.60\times10^{-10}$[c] | n.a. |
| Respirable suspended particulate (RSP) ($PM_{10}$) | kg | $1.98\times10^{-1}$[c] | $8.85\times10^{-2}$[f] |
| $CH_4$ (sewage sludge)<br>$CH_4$ (food waste)[a] | kg<br>kg | $9.7\times10^{-3}$[d]<br>$2.0\times10^{-4}$[d] | 5 % leakage of total biogas produced[d] |
| $N_2O$ (sewage sludge)<br>$N_2O$ (food waste)[a] | kg<br>kg | $9\times10^{-1}$[d]<br>$5\times10^{-2}$[d] | $1.38\times10^{-2}$[f] |
| Other parameters | | | |
| Fly ash | tonne | $3.6\times10^{-2}$[b] | n.a. |
| Bottom ash | tonne | $1.8\times10^{-1}$[b] | n.a. |
| Diesel consumption | MJ | 15.69[b] | n.a. |
| Gasoline consumption | MJ | 18.61[b] | n.a. |
| Digestate | tonne | n.a. | $3.1\times10^{-1}$[f] |
| Biogas (anaerobic digestion) | $m^3$ | n.a. | 125[f] |
| Biogas (anaerobic co-digestion) | $m^3$ | n.a. | 38.5[g] |
| Percentage of methane in biogas | % | n.a. | 60[h] |
| Lower heating value of methane | $kWh/m^3$ | n.a. | 10[i] |
| Generator efficiency | % | 20[e] | 48 (heat), 39 (electricity)[j] |

*n.a.* not applicable

[a] The food waste incineration data for $CH_4$ and $N_2O$ are assumed as "wet waste" defined by IPCC 2006

[b] Song et al. 2013

[c] Local emission data are unavailable. The data used in this study refer to the proposed incinerator in Hong Kong. The incinerator in Macau and the proposed incinerator in Hong Kong follow the emission standard set by the European Commission's Waste Incineration Directive. Under a conservative approach, the emission data of the study follow the emission standard as set by the Macau government, Woon and Lo 2014

[d] IPCC 2006

[e] Murphy and McKeogh 2004 (steam turbine)

[f] HKEPD 2009

[g] Ejlertsson and Magnusson 2013

[h] Krich et al. 2005

[i] Swedish Gas Centre 2012

[j] Streckienė et al. 2009; Pöschl et al. 2010; Bernstad and la Cour Jansen 2011 (averaging respective value, CHP unit)

with a global warming potential of 298 (Forster et al. 2007), causing the incineration of sewage sludge to be a big contributor to climate change.

Figure 3b demonstrates that scenario coAD (SS+FW) is the best performer in the particulate matter formation. During the anaerobic co-digestion process, the main environmental burden is contributed by respirable suspended particulates (RSP) emissions during the unloading and pre-processing of sewage sludge and food waste. A centralized air pollution control system is applied to treat the vented air from the processes according to the standard requirement stated in the EIA report before it is discharged to the atmosphere (HKEPD 2009). These emissions are comparatively lower than those generated from the incineration process, which contributes the highest burden on particulate matter formation in scenarios EI (SS+FW) and EI&AD (SS+FW). For incineration, the existing incineration plant complies with the

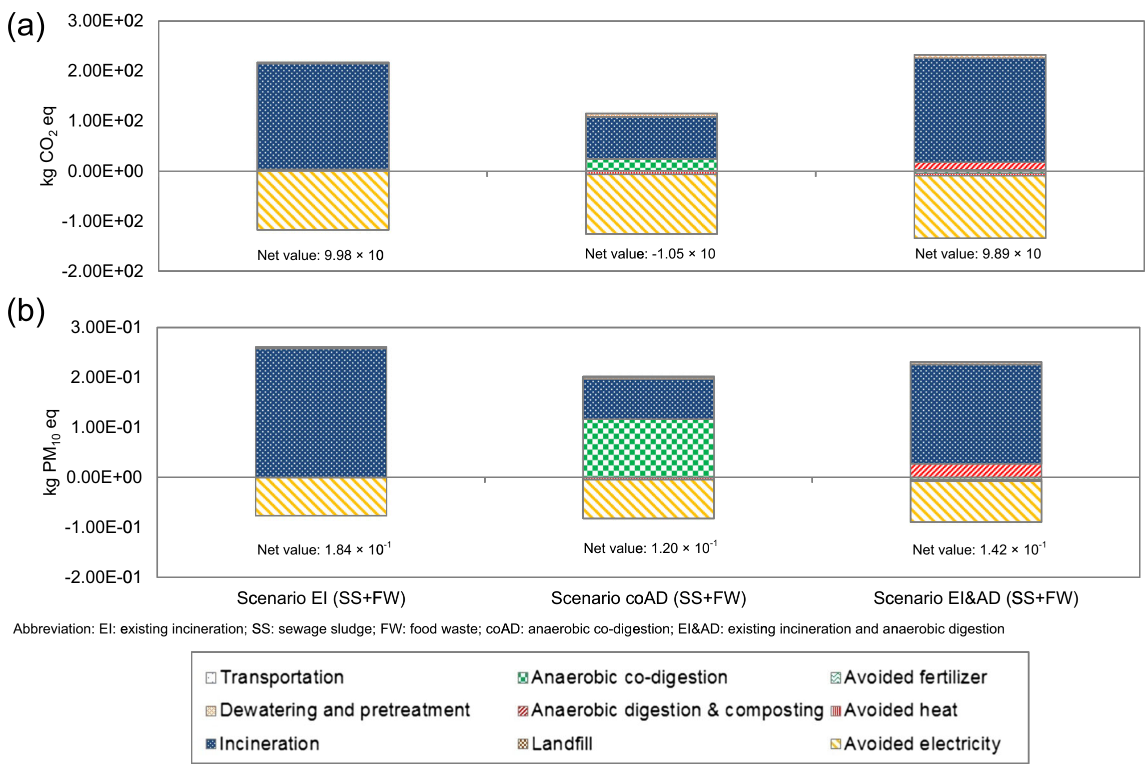
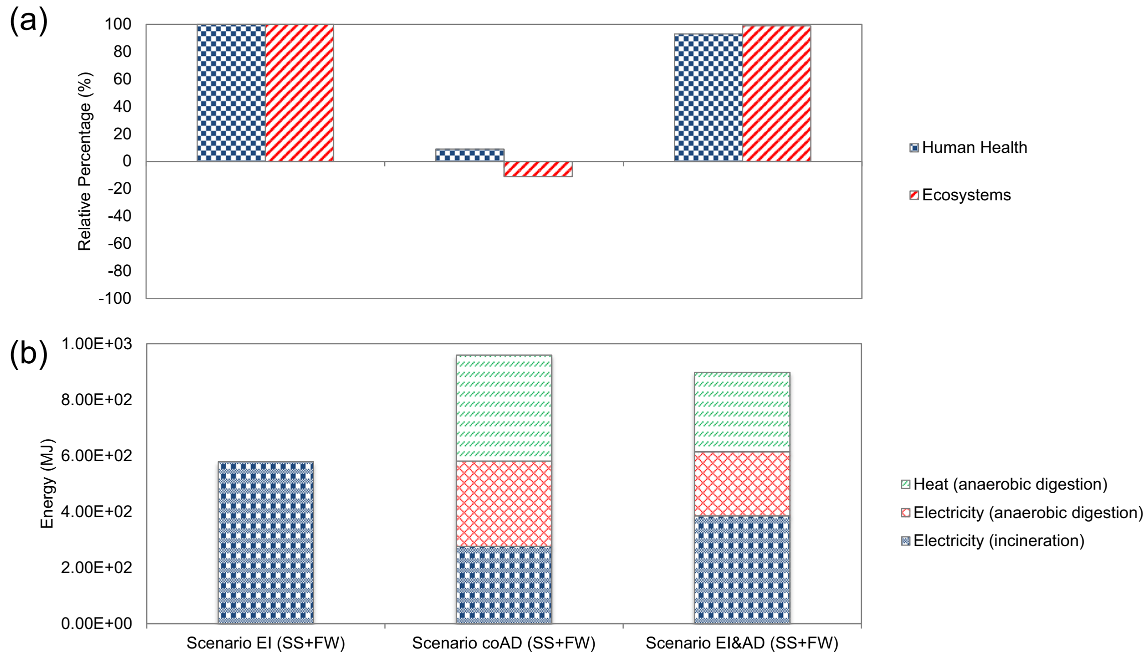



**Fig. 3** Comparison of environmental impacts in **a** climate change and **b** particulate matter formation per functional unit (i.e., 1 tonne of sewage sludge and food waste mixture with a 10:3 mixing ratio by wet weight) from different scenarios in part 1

directive 2000/76/EC, but still, RSP, $NO_x$, and $SO_2$ are emitted after treatment from the air pollution control unit. The emitted $NO_x$ and $SO_2$ are considered secondary particulate matter precursors which can react with water vapor and other chemicals to form fine particles in the atmosphere (Guerra et al. 2014), causing the formation of particulate matter. Moreover, for scenario coAD (SS+FW), a large amount of substrate is consumed by anaerobic co-digestion. The reliance on incineration for treating the remaining digestate is also lower compared to the other two scenarios, thus generating lower emissions. Hence, with all the above concerns, the direct particulate matter formation impact of scenario coAD (SS+FW) is the lowest.

### *3.1.2 Part 1: Interpretation of damage categories and energy performance*

The human health damages of scenario EI (SS+FW), coAD (SS+FW), and EI&AD (SS+FW) are $1.87\times10^{-4}$, $1.64\times10^{-5}$, and $1.75\times10^{-4}$ disability-adjusted life years (DALYs) and the ecosystems damage for these three scenarios are $7.88\times10^{-7}$, $-8.57\times10^{-8}$, and $7.80\times10^{-7}$ species-year, respectively. Figure 4a represents the relative percentage (i.e., the quotient of the respective absolute values divided by the highest absolute values of each damage category) comparison of human health and ecosystems damage categories among the three scenarios. A lower relative percentage indicates a lower environmental impact. From the results, scenario coAD (SS+FW) shows the best performance in terms of human health and ecosystems while scenario EI (SS+FW) performs the worst in both damage categories. Detailed results are presented in Table B.1–B.4 in the Electronic Supplementary Material. With regard to energy production performance, total energy production from scenario EI (SS+FW), coAD (SS+FW), and EI&AD (SS+FW) are $5.78\times10^2$, $9.60\times10^2$, and $8.98\times10^2$ MJ. Figure 4b indicates that scenario coAD (SS+FW) is the best among the three scenarios in part 1. Scenario coAD (SS+FW) produces 40 and 6.5 % more energy than scenarios EI (SS+FW) and EI&AD (SS+FW), respectively. Heat and electricity produced from the combined heat and power (CHP) unit of the anaerobic co-digestion process is the largest contributor of energy production, accounting for 71 % of the total energy production in scenario coAD (SS+FW). The CHP unit is highly compatible with anaerobic digestion processes as the biogas generated can be used as a fuel source and the heat produced satisfies the heat load demand by anaerobic digesters (USEPA 2011). It is suggested that the two proposed scenarios whereby anaerobic digestion involved can bring a great




Abbreviation: EI: existing incineration; SS: sewage sludge; FW: food waste; coAD: anaerobic co-digestion; EI&AD: existing incineration and anaerobic digestion

**Fig. 4** Indicator comparison in **a** relative percentage comparison for damage categories as human health and ecosystems and **b** energy recovery performance in terms of total energy production per functional unit (i.e., 1 tonne of sewage sludge and food waste mixture with a 10:3 mixing ratio by wet weight) from different scenarios in part 1

benefit in terms of energy production performance. It has been suggested that the biogas generated from anaerobic co-digestion can be altered by varying the mixing ratio between sludge and food waste (Kim et al. 2003). The local government should further study the ratio applied for co-digestion in order to maximize the biogas production.

### 3.2 Part 2: Selection of scenarios for the remaining food waste treatment in Macau

#### *3.2.1 Part 2: Midpoint comparison in climate change and particulate matter formation*

In terms of both climate change and particulate matter formation, scenario AD (FW) is also a better waste treatment scenario for treating the remaining food waste. It has a total value of $-1.54\times10^{2}$ kg $CO_2$ eq. and $-3.42\times10^{-2}$ kg $PM_{10}$ eq. (Fig. 5), which indicate its environmental benefits over incineration.

Figure 5a shows the environmental burden contribution to climate change by different processes in scenario EI (FW) and AD (FW). The major direct emission in scenario AD (FW) is from the anaerobic digestion process in which biogas leaks as fugitive emission. The environmental burden contributed by incineration is low since the combustion of food waste produces less greenhouse gases (mainly $N_2O$) than that of sewage sludge. Although scenario AD (FW) has greater direct emissions, its avoided emissions are greater than those in scenario EI (FW). Indeed, more energy and compost are generated from the anaerobic digestion process, bringing greater environmental benefits to scenario AD (FW).

#### *3.2.2 Part 2: Interpretation of damage categories and energy performance*

The human health damages of scenario EI (FW) and AD (FW) are $-1.75\times10^{-4}$ and $-2.25\times10^{-4}$ DALYs, and the ecosystems damage for these two scenarios are $-1.21\times10^{-6}$ and $-1.23\times10^{-6}$ species-year, respectively. The relative comparison of human health and ecosystems damage categories for scenario EI (FW) and scenario AD (FW) is presented in Fig. 6a. From the results, scenario AD (FW) is advantageous over scenario EI (FW) with greater environmental benefits in damage categories. The total energy production from scenario EI (FW) and AD (FW) are $8.40\times10^{2}$ and $2.22\times10^{3}$ MJ. Figure 6b demonstrates that the total energy production from scenario AD (FW) is higher than that of scenario EI (FW). The higher energy production in anaerobic digestion compared with that of incineration was also substantiated by Khoo et al. (2010). This paper examined both incineration and anaerobic digestion treatment of food waste in Singapore and found that anaerobic digestion of food waste has an impressive net energy generation. According to the results in part 2, scenario AD (FW) is proposed for treating the remaining food waste in

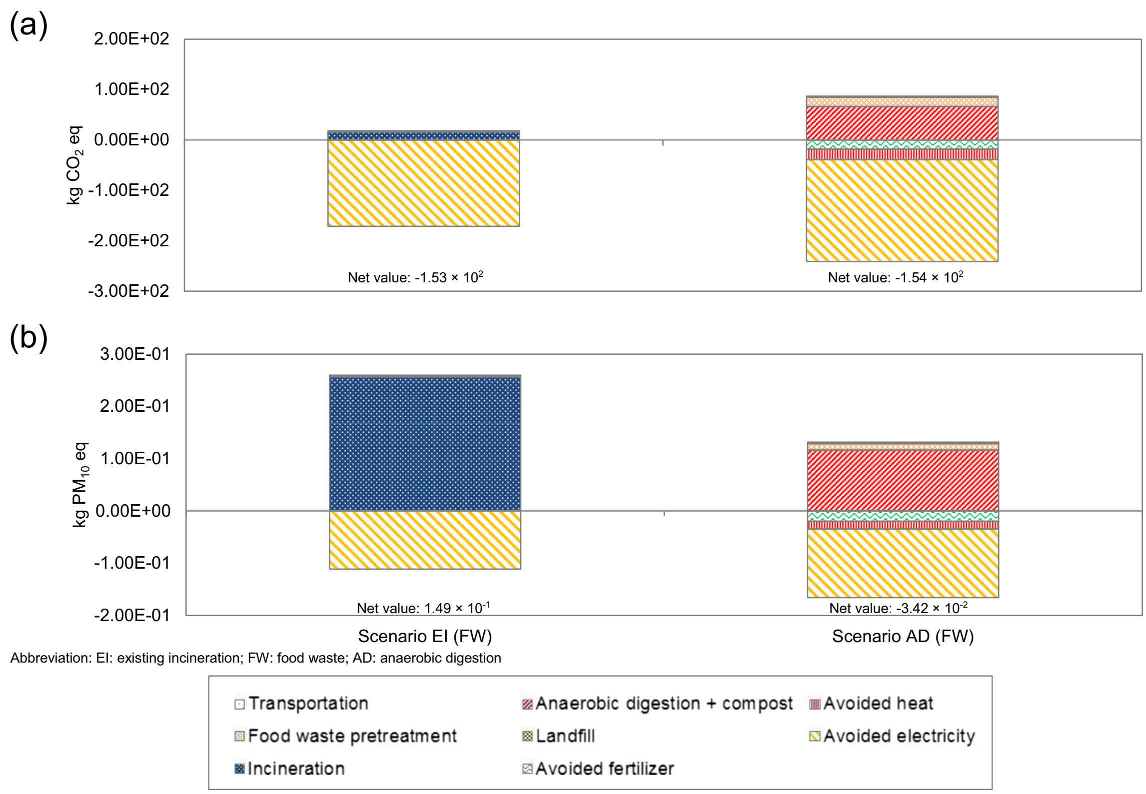



**Fig. 5** Comparison of environmental impacts in **a** climate change and **b** particulate matter formation per functional unit (i.e., 1 tonne of remaining food waste) from different scenarios in part 2

Macau. The detailed results are presented in Table B.5–B.8 in the Electronic Supplementary Material.

### 3.3 Part 3: Identification of a waste treatment strategy for treating all sewage sludge and food waste generated in Macau

In this section, a waste treatment strategy for treating sewage sludge and food waste in Macau is identified. The strategy comprises a combination of waste treatment methods based on the results from part 1 and part 2. In part 1, scenario coAD (SS+FW) is selected to treat sewage sludge and food waste. In part 2, scenario AD (FW) is selected to treat the remaining food waste. A proposed scenario namely scenario PS (all) is formed involving the two proposed methods for treating all sewage sludge and food waste produced in Macau each day (Table 3). It is then compared with the existing incineration scenario, namely scenario EI (all).

#### *3.3.1 Part 3: Comparison between the existing incineration scenario and proposed scenario for treating all sewage sludge and food waste*

The human health damages of scenario EI (all) and PS (all) are $-2.99\times10^{-2}$ and $-4.89\times10^{-2}$ DALYs, and the ecosystems damage for these two scenarios are $-2.31\times10^{-4}$ and $-2.75\times10^{-4}$ species-year, respectively. As indicated in Fig. 7a, scenario PS (all) performs better than scenario EI (all) in both human health and ecosystems damage categories with 36 and 13 % differences, respectively. From Fig. 7b, the total energy production from scenario PS (all) is $5.33\times10^{5}$ MJ, which is 61 % higher than that from scenario EI (all). Based on the comparison, scenario PS (all) has better performance in all indicators assessed for sewage sludge and food waste treatment than scenario EI (all). The detailed results are presented in Table B.9–B.11 in the Electronic Supplementary Material.

Although scenario PS (all) shows advantages in both environmental and energy production performance, the amount of substrates (i.e., sewage sludge and food waste) treated by scenario coAD (SS+FW) is not large as shown in Table 3, leaving a large amount of food waste to be treated by scenario AD (FW). It may not be economically viable to build an anaerobic co-digestion plant with such a low treatment capacity currently. However, the wastewater treatment plants in Macau will be upgraded according to the Environmental Protection Planning of Macau (2010–2020) (DSPA 2012). Due to the increased wastewater treatment capacity, the projected amount of sewage sludge generated will be increased from 30 to 242 tpd according to an unpublished report provided by the Macau government. Hence, further comparison is performed for the condition with increased sewage sludge. Two scenarios,

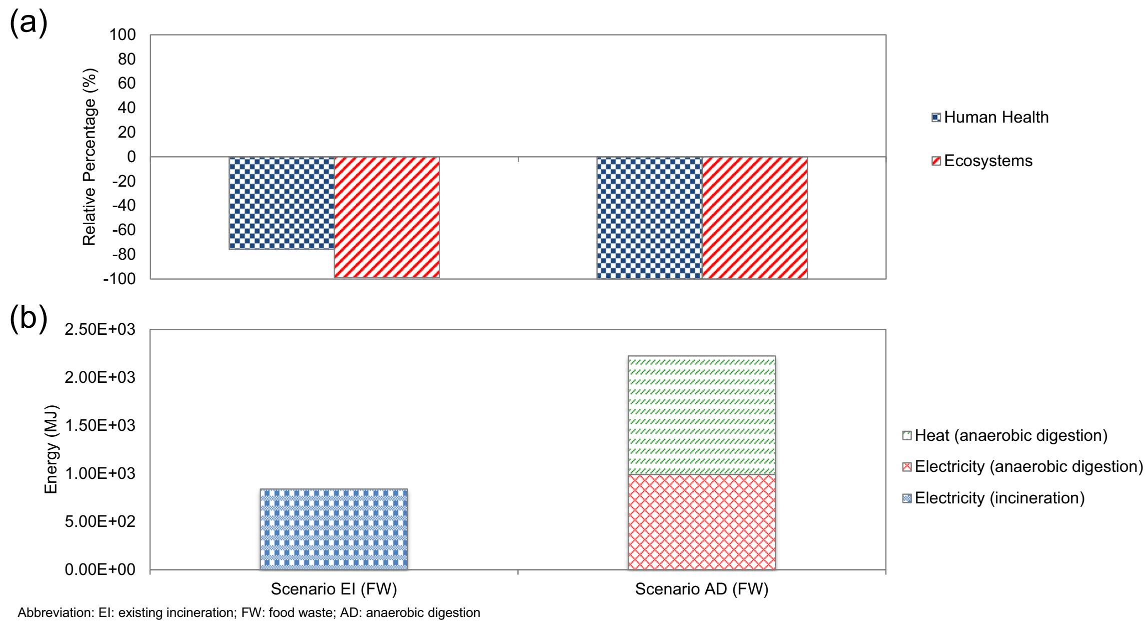



**Fig. 6** Indicator comparison in **a** relative percentage comparison for damage categories as human health and ecosystems and **b** energy recovery performance in terms of total energy production per functional unit (i.e., 1 tonne of remaining food waste) from different scenarios in part 2

namely scenario EI (all+increased SS) and scenario PS (all+increased SS) are defined and the descriptions of each scenario are shown in Table 1. The total amount of sewage sludge and food waste that can be treated after the wastewater treatment plants are upgraded is shown in Table 3.

*3.3.2 Part 3: Comparison between the existing incineration scenario and proposed scenario for increased sewage sludge*

Regarding environmental performance, comparisons between the existing incineration scenario and the proposed scenario for the condition with increased sewage sludge in human health and ecosystems damage categories are shown in Fig. 8a. The human health damages of scenario EI (all+increased SS) and PS (all+increased SS) are $3.12\times10^{-2}$ and $-3.06\times10^{-2}$ DALYs, and the ecosystems damage for these two scenarios are $5.35\times10^{-5}$ and $-2.22\times10^{-4}$ species-year, respectively. Scenario PS (all+increased SS) performs better than scenario EI (all+increased SS) in both human health and ecosystems damage categories with 198 and 125 % differences, respectively. The major reason for such huge differences is that using anaerobic co-digestion to treat the increased amount of sewage sludge in scenario PS (all+increased SS) produces lower environmental burdens compared to

**Table 3** Amount of sewage sludge and food waste treated by the waste treatment methods selected from part 1 and part 2 in both current and future situations

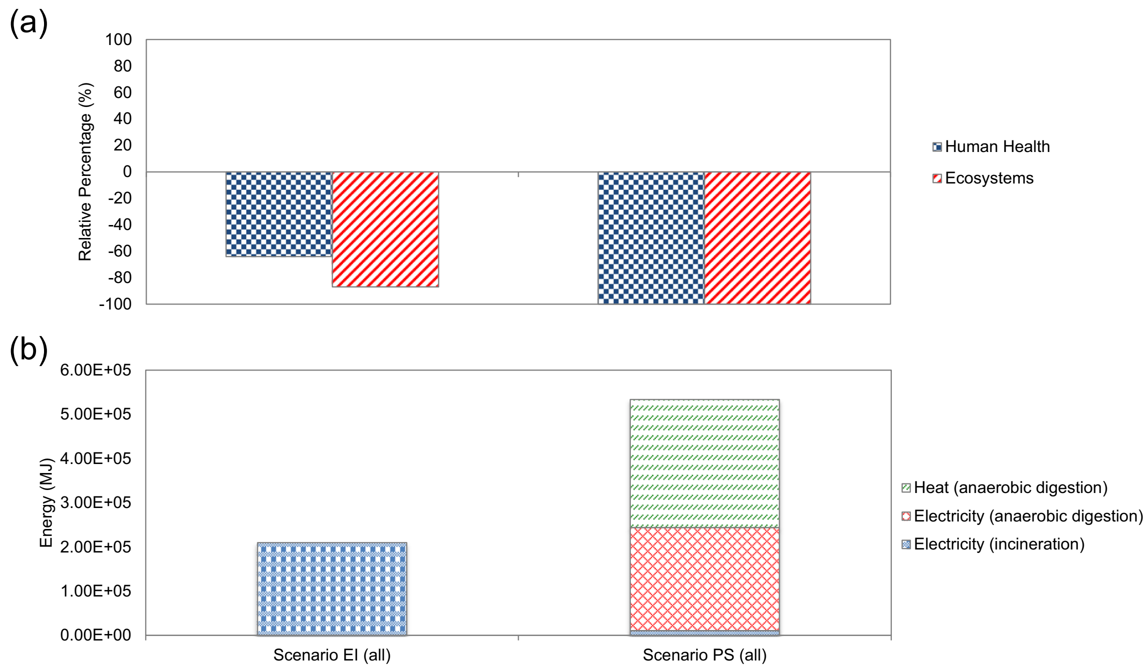
| | | Current situation (wastewater treatment plants are not upgraded) | | Future situation (wastewater treatment plants are upgraded) | |
|---|---|---|---|---|---|
| | Unit | Sewage sludge[a] | Food waste | Sewage sludge | Food waste |
| Total amount of sewage sludge and food waste treated by scenario coAD (SS+FW)[b] | tpd | 30 | 9 | 242[c] | 73 |
| Total amount of remaining food waste treated by scenario AD (FW) | tpd | n.a. | 223 | n.a. | 159 |
| Total amount of sewage sludge and food waste generated in Macau | tpd | 30 | 232 | 242 | 232 |

*n.a.* not applicable

[a] Dry matter content of dewatered sewage sludge is around 20–30 %. In this study, the dewatered sewage sludge is assumed to be 30 % dry matter content (EEA 1998)

[b] Mixing ratio of sewage sludge to food waste is equal to 10:3 by wet weight

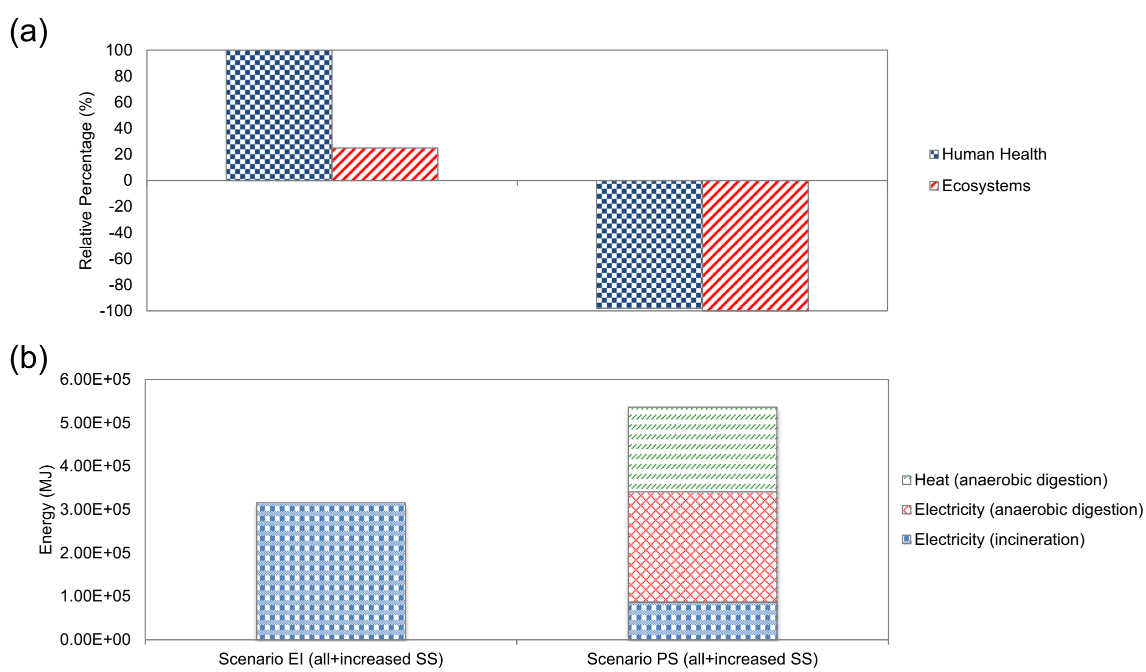
[c] Projected amount of sewage sludge after upgrading of sewage treatment plants in Macau




Abbreviation: EI: existing incineration; all: all sewage sludge and food waste generated currently; PS: proposed scenario

**Fig. 7** Indicator comparison in **a** relative percentage comparison for damage categories as human health and ecosystems and **b** energy recovery performance in terms of total energy production per functional unit (i.e., all sewage sludge and food waste generated currently) from different scenarios in part 3

incineration in scenario EI (all+increased SS) by reducing the $N_2O$ emissions from the incineration process. For energy production performance, as shown in Fig. 8b, the total energy production from scenario PS (all+increased SS) is higher than that of scenario EI (all+increased SS) by 41 %. Considering the treatment capacity and all the benefits of scenario PS (all+




Abbreviation: EI: existing incineration; all+increased SS: all sewage sludge and food waste generated after wastewater treatment plants are upgraded; PS: proposed scenario

**Fig. 8** Indicator comparison in **a** relative percentage comparison for damage categories as human health and ecosystems and **b** energy recovery performance in terms of total energy production per functional unit (i.e., all sewage sludge and food waste generated after wastewater treatment plants are upgraded) from different scenarios in part 3 increased SS), it is suggested that this scenario is a feasible and sustainable waste treatment strategy for the treatment of sewage sludge and food waste after the wastewater treatment plants are upgraded in the future.

## 4 Conclusions

This study proposes a sustainable waste treatment strategy for sewage sludge and food waste treatment by comparing the environmental impacts and energy production performance among different waste treatment scenarios using LCA methodology. Current treatment method by incineration (i.e., sewage sludge and food waste combusted with MSW) and two proposed treatment methods, namely anaerobic co-digestion and anaerobic digestion, are included in the waste treatment scenarios. With respect to the midpoint environmental impacts, climate change and particulate matter formation are the most significant impacts caused by the process. By comparing all scenarios, anaerobic co-digestion of sewage sludge and food waste was found to be more favorable in Macau, as the waste treatment method there incurs the lowest environmental impacts and the highest energy production performance. Since all the sewage sludge is consumed after anaerobic co-digestion, while the remaining food waste is suggested to be treated by anaerobic digestion. The proposed scenario that incorporates anaerobic co-digestion and anaerobic digestion improves the performance in human health, ecosystems, and energy production by 36, 13, and 61 %, respectively, compared with the existing incineration scenario for treating all sewage sludge and food waste generated in Macau. In addition, a further study is conducted with increased generation of sewage sludge. The result shows that the proposed scenario is a better choice even if the amount of sewage sludge increases after the wastewater treatment plants are upgraded. The environmental performance of proposed scenario is almost two times better than the existing incineration scenario in human health damage. With the convincing result of LCA, it is believed that this study can shed light upon the applicability of policy framework for sewage sludge and food waste treatment in urbanized cities from environmental and energy production perspective.

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